

Weak Mixing Angle at LHC and CMS Experience

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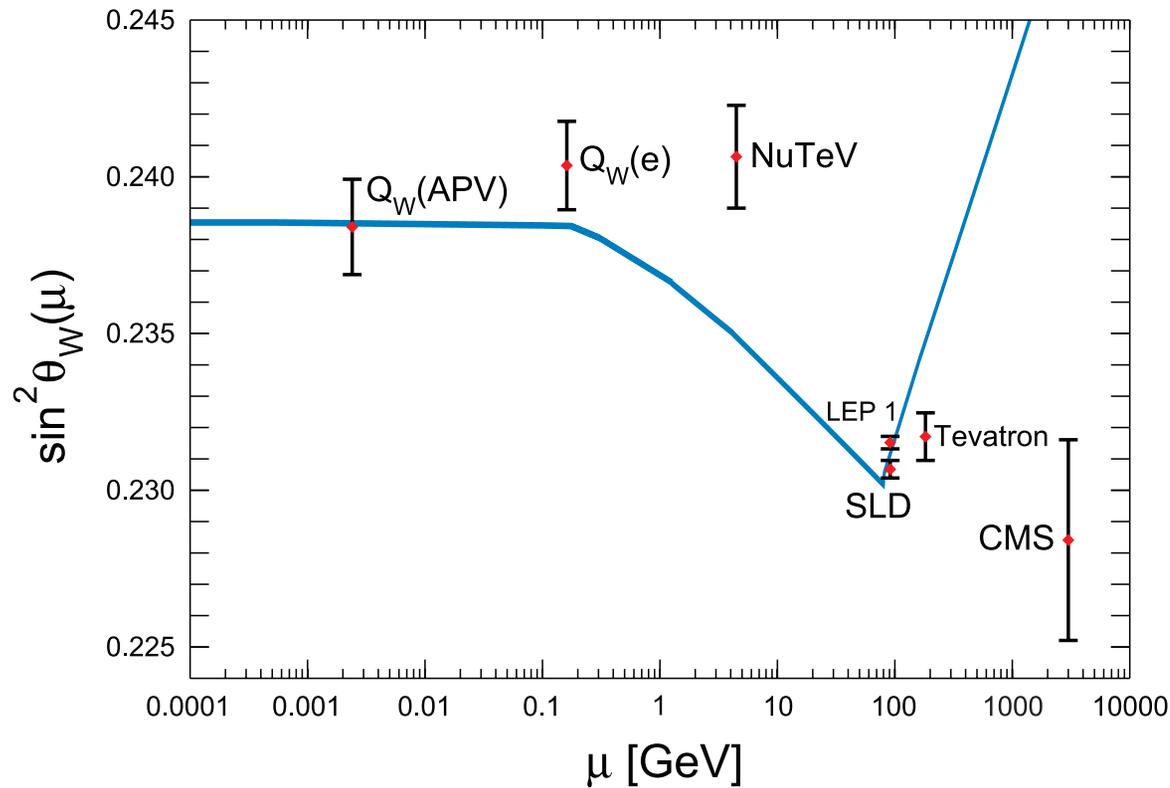
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Electroweak Study Group
Snowmass Energy Frontier Workshop

Brookhaven National Laboratory, Upton, NY

Introduction

PDG 2012



- see CMS, [Phys. Rev. D 84, 112002 \(2011\)](#) 1.1 fb⁻¹ of 7 TeV data
 $\sin^2 \theta_{\text{eff}} = 0.2287 \pm 0.0020$ (*stat.*) ± 0.0025 (*syst.*)
- details Ph.D. thesis by N. Tran (JHU): [CERN-THESIS-2011-127](#)
 - “Angles and Daemons: Spin Correlations at the LHC”
 - testing ground for Higgs MELA approach

$\sin^2 \theta_W$ and A_{FB}

$$\hat{\sigma}_{q\bar{q}}(s = m_{\ell\ell}^2, \theta^*) \propto \frac{1}{s} \sum_{\chi_1, \chi_2, \lambda_1, \lambda_2 = \uparrow\downarrow} \left(d_{\chi_1 - \chi_2, \lambda_1 - \lambda_2}^{J=1}(\theta^*) \right)^2 \times$$

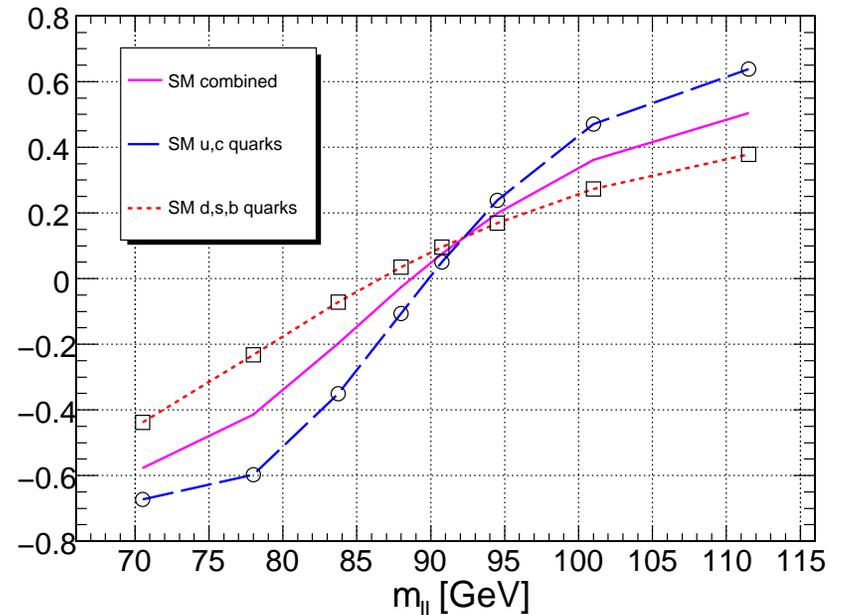
$$\left| A_{\lambda_1, \lambda_2}^{(\gamma \rightarrow \ell\ell)} B_{\chi_1, \chi_2}^{(q\bar{q} \rightarrow \gamma)} + A_{\lambda_1, \lambda_2}^{(Z \rightarrow \ell\ell)}(\theta_W) B_{\chi_1, \chi_2}^{(q\bar{q} \rightarrow Z)}(\theta_W) \times \frac{s}{(s - m_Z^2) + im_Z \Gamma_Z} \right|^2$$

$$\propto \frac{3}{8} (1 + \cos^2 \theta^*) + A_{FB}^{q\bar{q}}(s, \theta_W) \cos \theta^*$$

• measure $A_{FB} \Leftrightarrow$ measure $\sin^2 \theta_W$

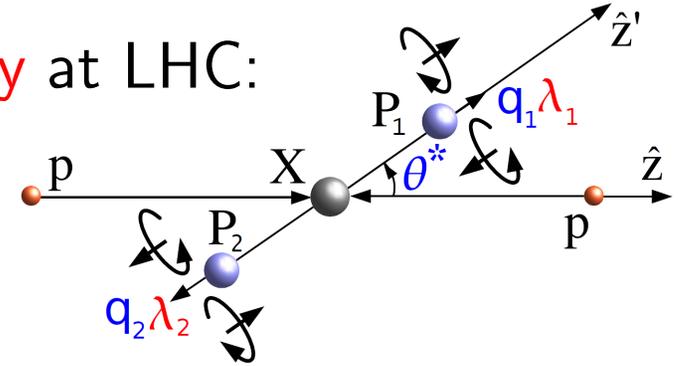
• A_{FB} depends on

- q flavor (7 TeV pp $\sim 50\%$ $u + c$) A_{FB}
- mass $s = m_{\ell\ell}^2$
- $\sin^2 \theta_W$ (or c_V & c_A)



Challenge 1: Partons and Their Dilution

- Problem on LHC: PDF of quarks and symmetric initial pp state
 - rescued by boost (rapidity Y): prefer u and d quark direction
 - larger systematics from PDFs...
- Solved quark direction challenge **analytically** at LHC:



$$\frac{d\sigma_{\text{observe}}(Y, s, \theta^*; \vec{\zeta})}{dY ds d\cos\theta^*} \propto$$

$$\sum_{q=udscb} [\hat{\sigma}_{q\bar{q}}^{\text{even}}(s, \cos^2\theta^*) + D_{q\bar{q}}(s, Y) \times \hat{\sigma}_{q\bar{q}}^{\text{odd}}(s, \cos^1\theta^*)] \times F_{q\bar{q}}(s, Y)$$

$$D_{q\bar{q}}(s, Y) = \frac{\tilde{f}_q(e^{+|Y|}\sqrt{s/s_{pp}}, s) \tilde{f}_{\bar{q}}(e^{-|Y|}\sqrt{s/s_{pp}}, s) - \tilde{f}_q(e^{-|Y|}\sqrt{s/s_{pp}}, s) \tilde{f}_{\bar{q}}(e^{+|Y|}\sqrt{s/s_{pp}}, s)}{\tilde{f}_q(e^{+Y}\sqrt{s/s_{pp}}, s) \tilde{f}_{\bar{q}}(e^{-Y}\sqrt{s/s_{pp}}, s) + \tilde{f}_q(e^{-Y}\sqrt{s/s_{pp}}, s) \tilde{f}_{\bar{q}}(e^{+Y}\sqrt{s/s_{pp}}, s)}$$

$$F_{q\bar{q}}(s, Y) = \tilde{f}_q(e^{+Y}\sqrt{s/s_{pp}}, s) \tilde{f}_{\bar{q}}(e^{-Y}\sqrt{s/s_{pp}}, s) + \tilde{f}_q(e^{-Y}\sqrt{s/s_{pp}}, s) \tilde{f}_{\bar{q}}(e^{+Y}\sqrt{s/s_{pp}}, s)$$

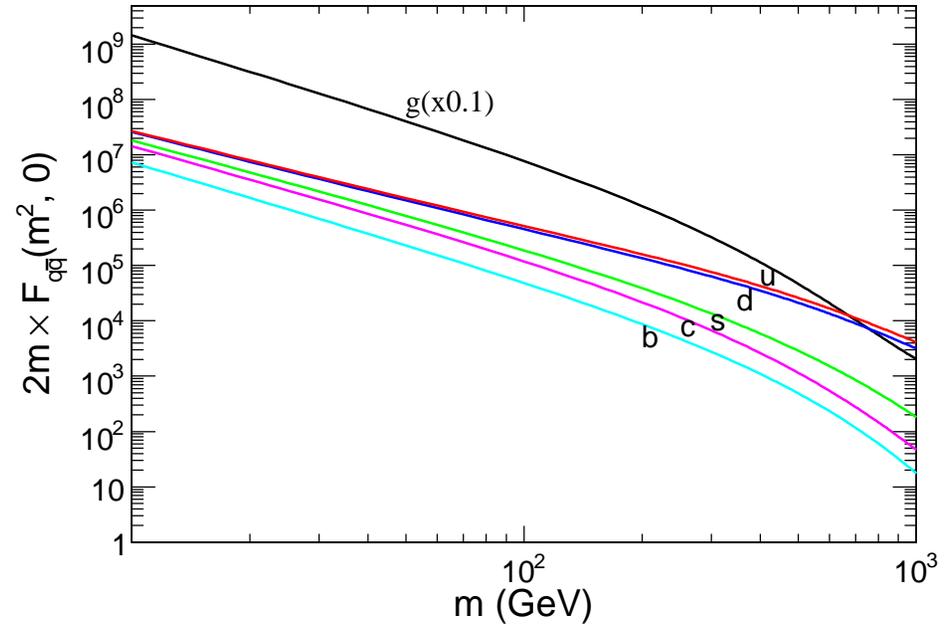
PDF Model: Parton Luminosity and Dilution

- Parton Luminosity Factor

$$F_{q\bar{q}}(s, Y)$$

u, d, s, c, b for $\gamma^*/Z/Z'$

(gg for Higgs)



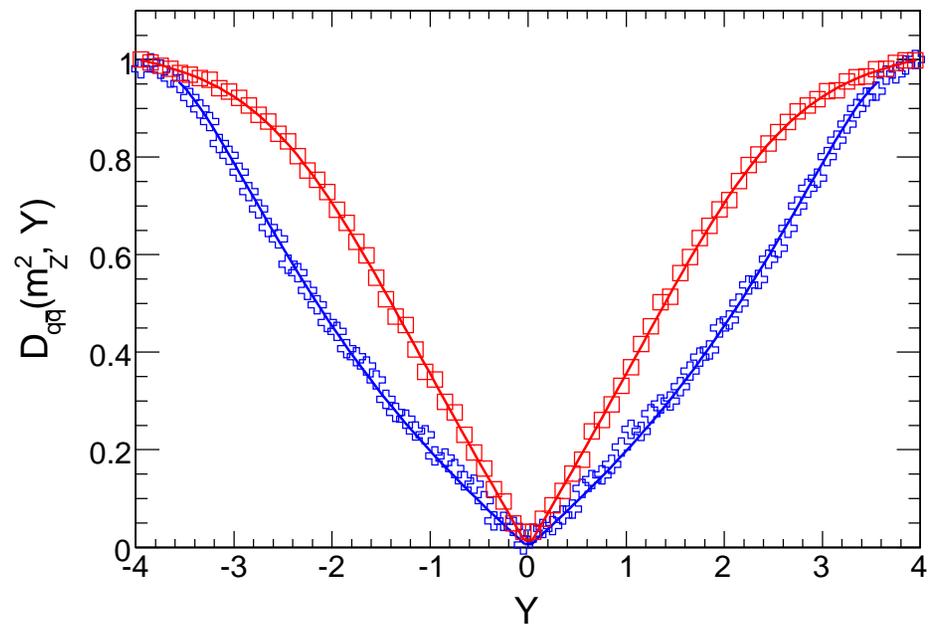
- Parton Dilution Factor

$$D_{q\bar{q}}(s, Y)$$

plot model against LO MC

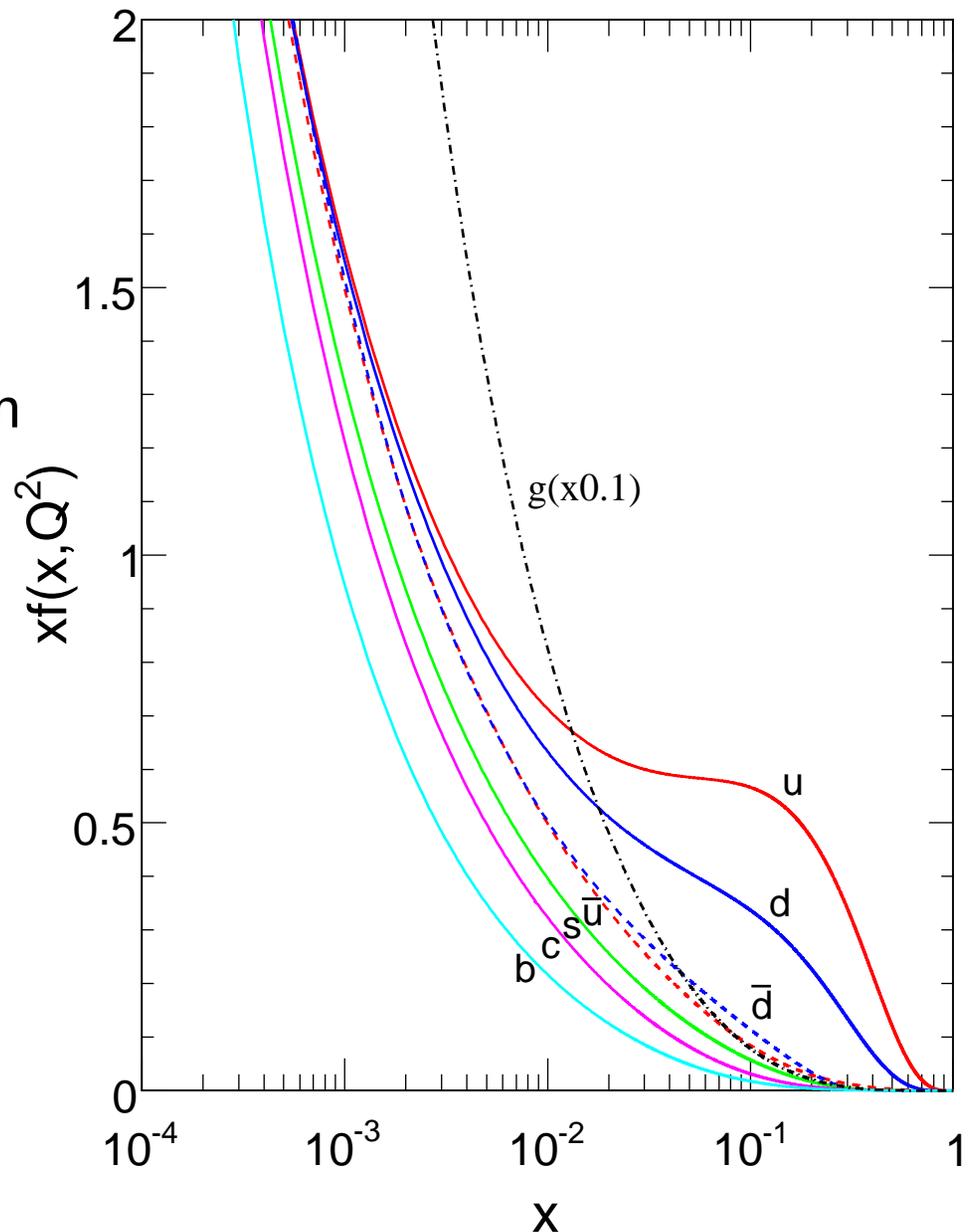
u and d

$D_{q\bar{q}} = 0$ for $q = s, c, b$



Model: Parton Distribution Functions

- PDF $\tilde{f}_{q,\bar{q}}(x, Q^2)$
extracted from CTEQ6
and described analytically
→ **fast** and **easy** implementation
- tried direct numerical approach
→ MUCH **slower**
with **similar** results
- Plot at $Q = 100$ GeV



LO Model: PDF(QCD) and EWK

- Each flavor matches well, plot analytical distribution vs LO MC

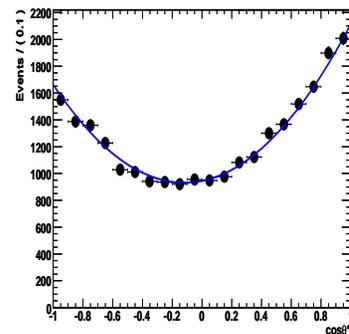
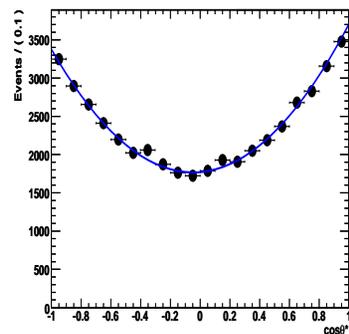
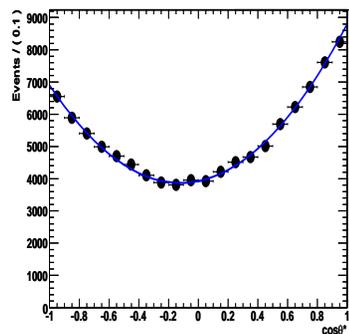
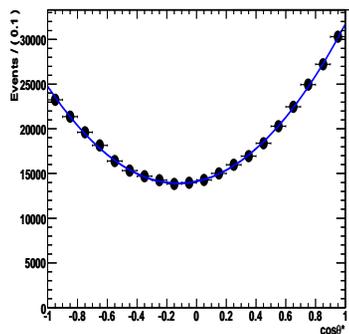
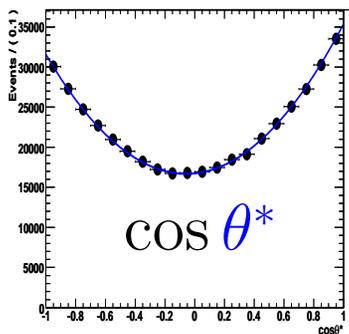
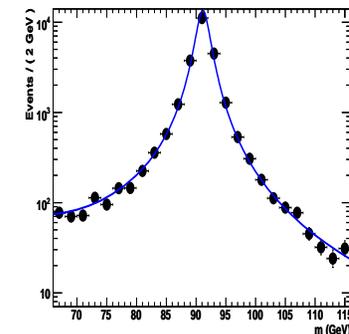
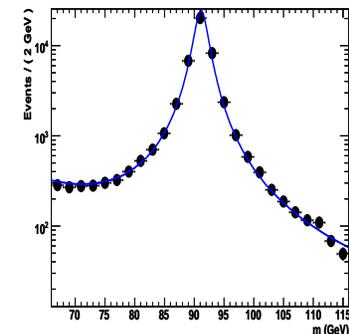
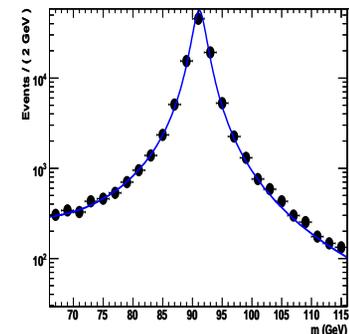
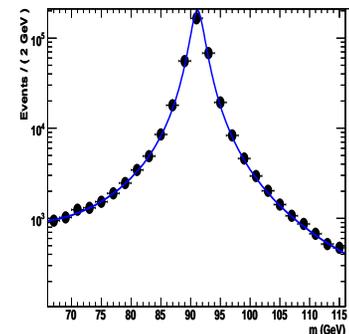
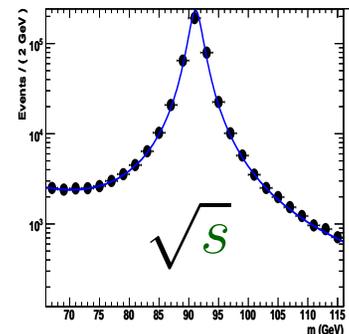
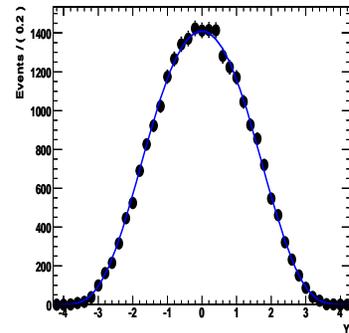
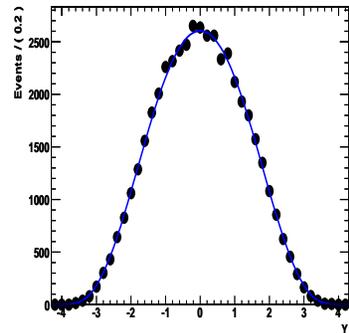
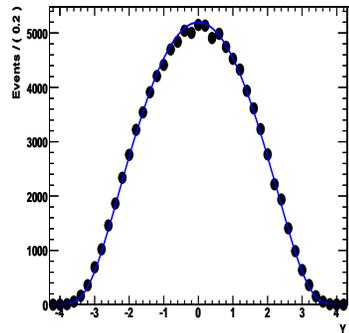
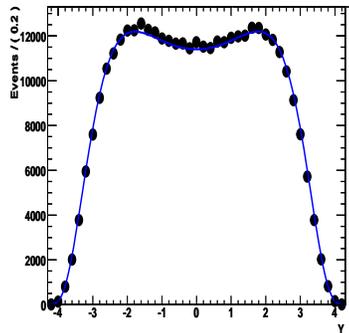
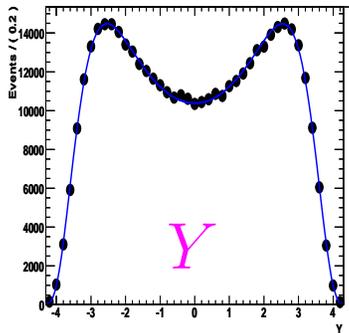
$u\bar{u}$ (45.7%)

$d\bar{d}$ (36.8%)

$s\bar{s}$ (10.2%)

$c\bar{c}$ (4.9%)

$b\bar{b}$ (2.5%)



Challenge 2: Detector Effects

- Lepton requirements (in CS frame*):

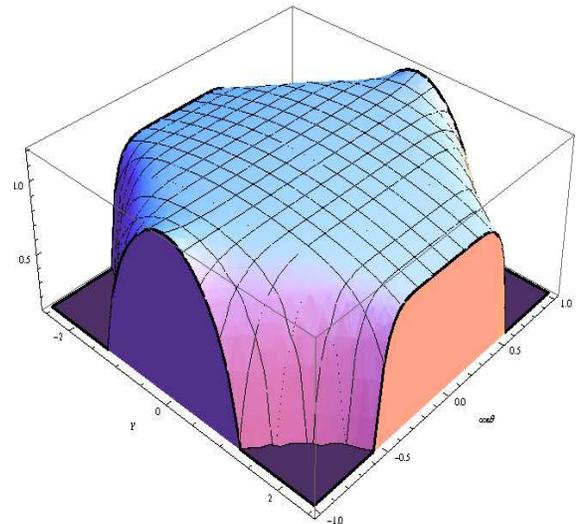
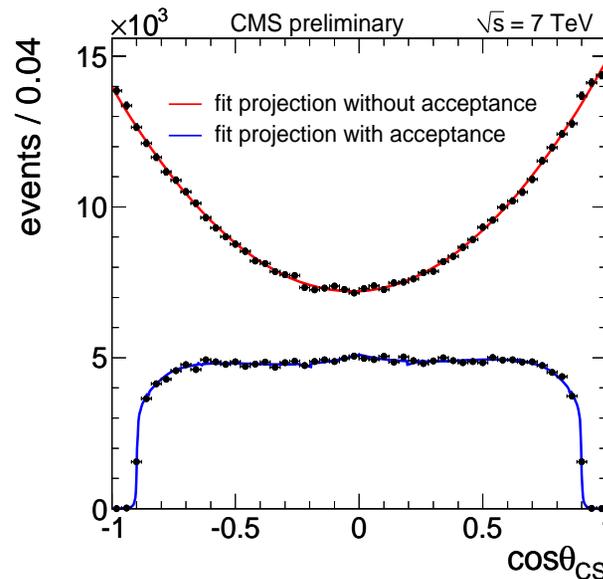
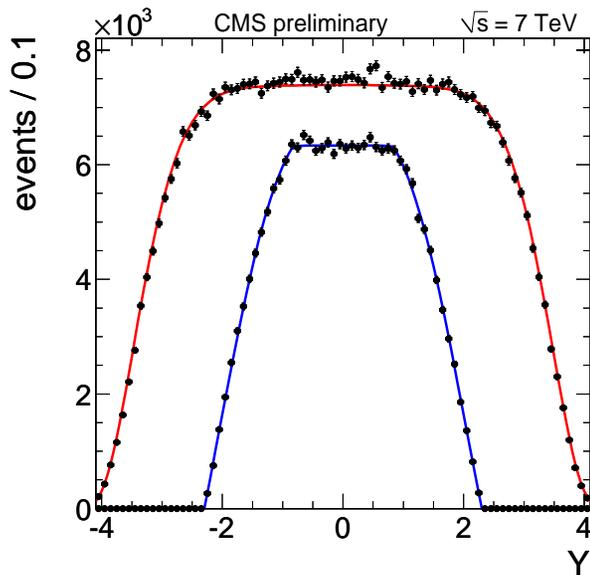
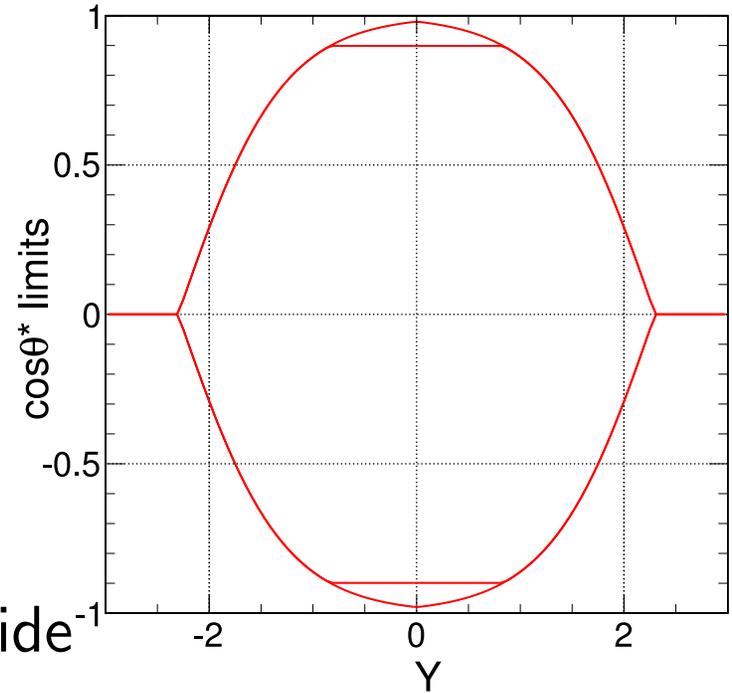
consider only $\mu^- \mu^+$ here

$$|\eta^*| < 2.3 \ \& \ |p_T^*| > 18 \text{ GeV} = p_{\min}$$

$$\Rightarrow |\cos \theta^*| < \tanh(Y_{\max} - |Y|)$$

$$\Rightarrow |\cos \theta^*| < \sqrt{1 - (2p_{\min}/m)^2}$$

$\mathcal{G}(\theta^*, Y, m) = 0$ outside, efficiency inside



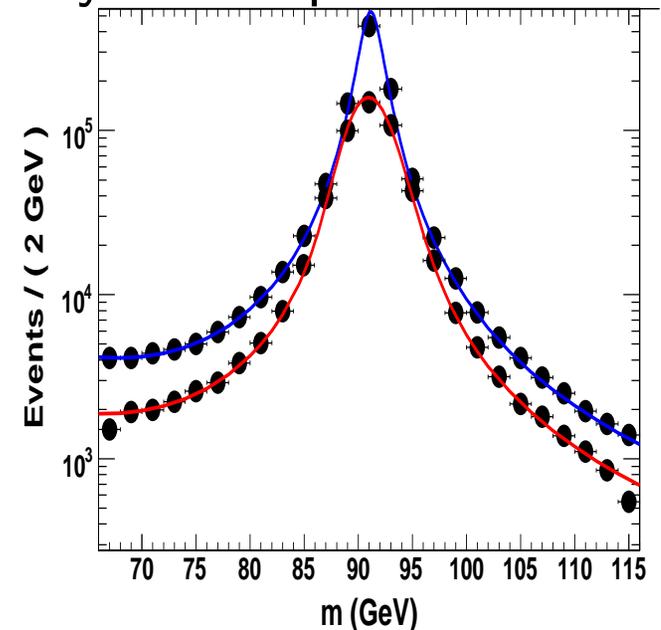
Challenge 3: FSR(QED) and NLO(QCD) Modeling

- Resolution and FSR: empirical many-Gaussian function $\mathcal{R}(x)$

$$\mathcal{P}_{\text{detect}}(\theta^*, Y, s) = \mathcal{G}(\theta^*, Y, s) \times \int_{-\infty}^{+\infty} dx \mathcal{R}(x) \mathcal{P}_{\text{observe}}(Y, s - x, \theta^*)$$

Roofit analytical implementation

- $\mathcal{R}(x)$ includes:
 - detector resolution and energy scale from simulation (GEANT)
float energy scale in data ("m_Z")
alignment/calibration studies – syst.
 - Final State Radiation (FSR)
from simulation (Pythia)
alternative models (PHOTOS, Horace) – systematics
80 < m < 100 GeV to reduce systematics



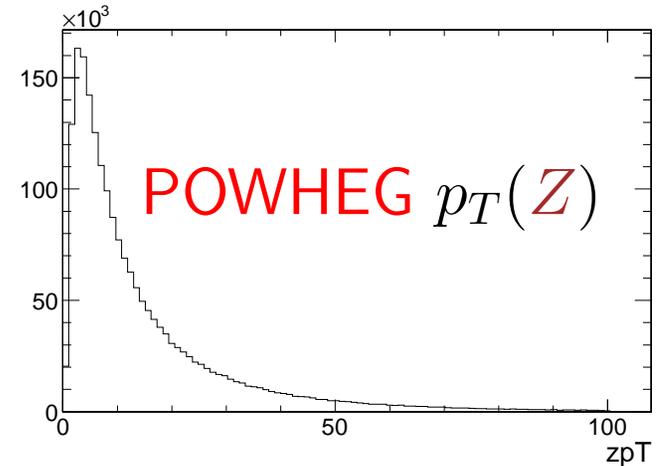
NLO(QCD) Modeling

- Test with NLO generator (**POWHEG**)

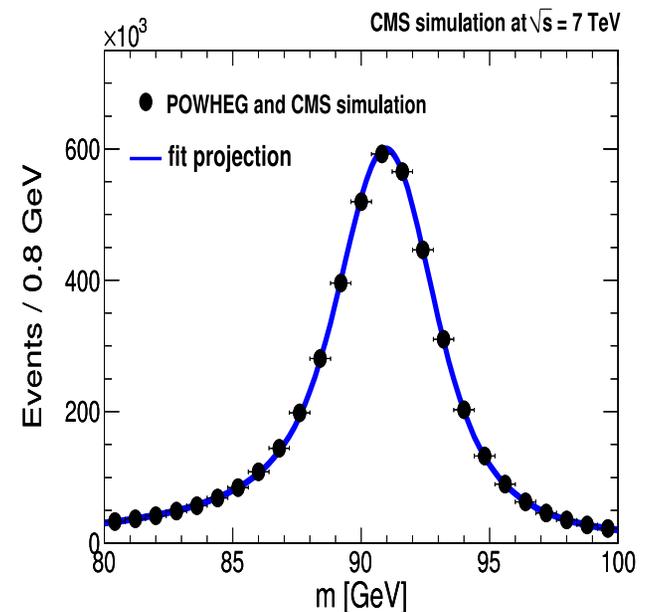
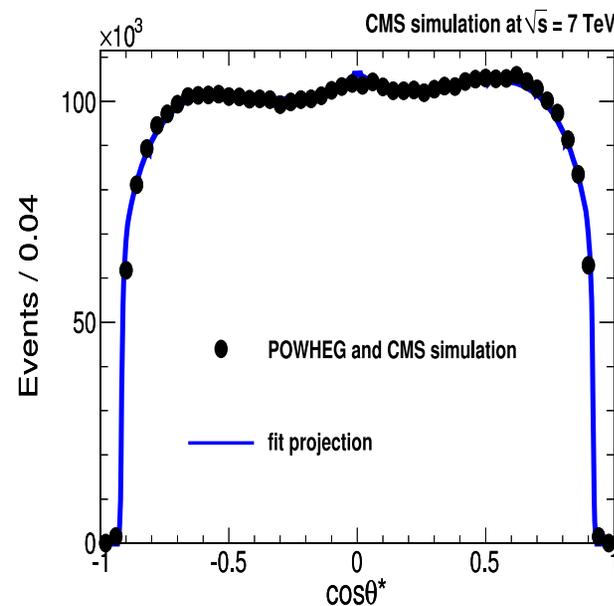
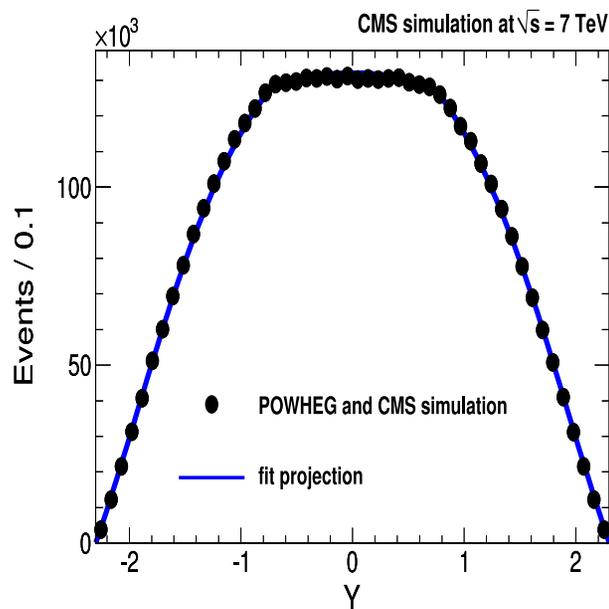
– suppress ISR(QCD) effects

$$p_T(\mu^- \mu^+) < 25 \text{ GeV}$$

result deviations – systematics (correction)



- NLO (**POWHEG**) + CMS (**GEANT**) simulation against 3D Model:



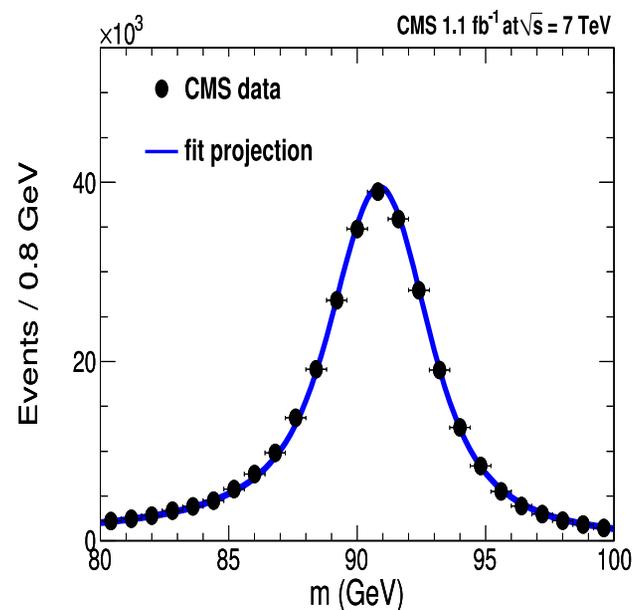
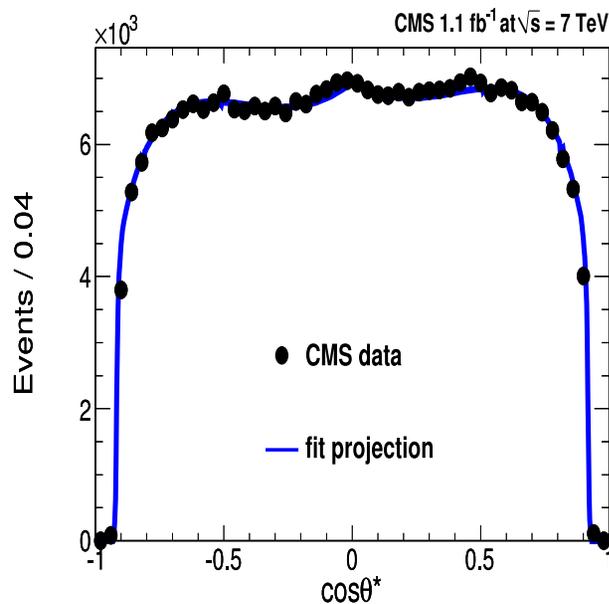
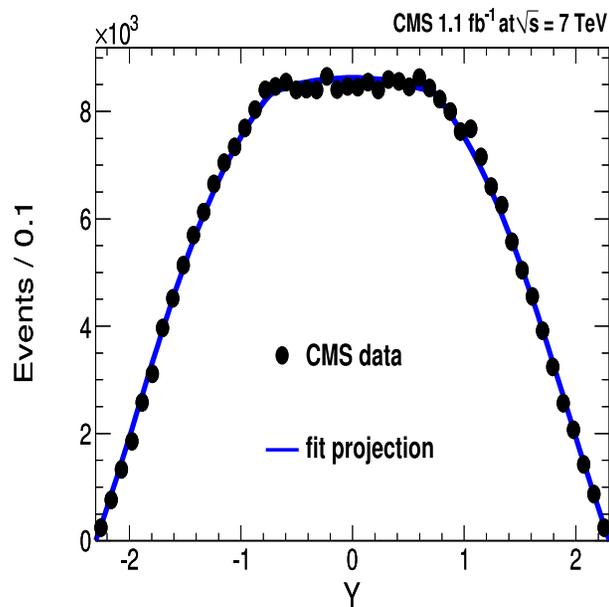
CMS Result (2011)

- Fit $\sin^2 \theta_{\text{eff}}$ with 1.07 fb^{-1} of CMS data at 7 TeV (297 364 events):

using $u\bar{u}$ & $d\bar{d} \rightarrow Z/\gamma^* \rightarrow \mu^-\mu^+$

$$\sin^2 \theta_{\text{eff}} = 0.2287 \pm 0.0020 \text{ (stat.)} \pm 0.0025 \text{ (syst.)}$$

- 1D projections of CMS data and 3D model:



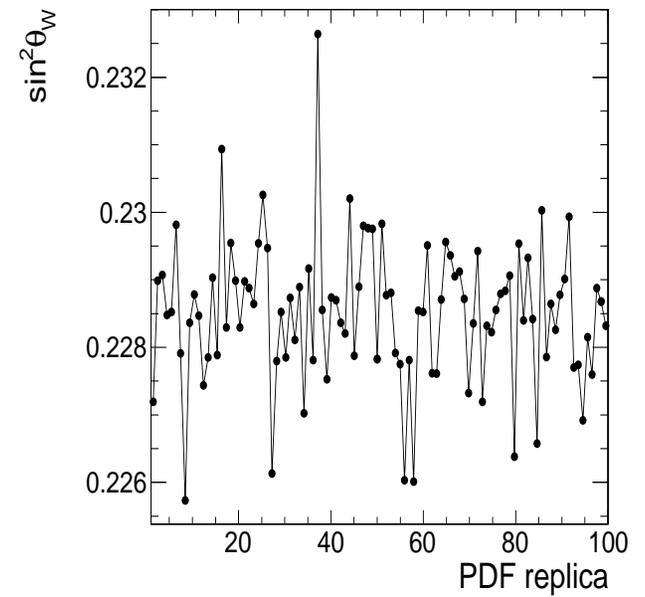
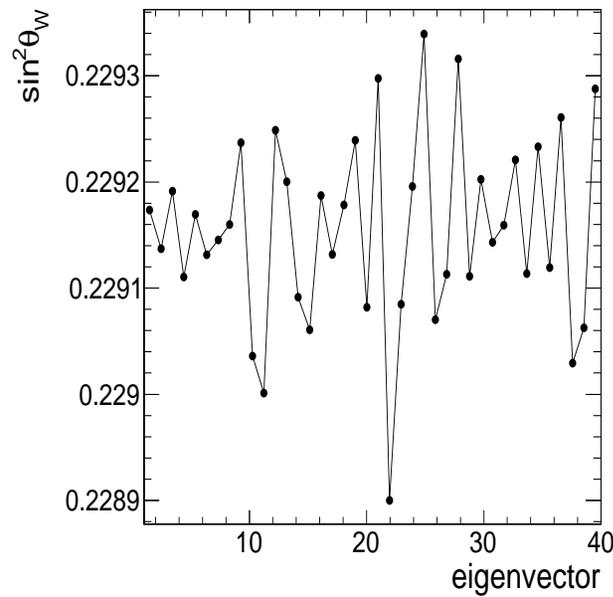
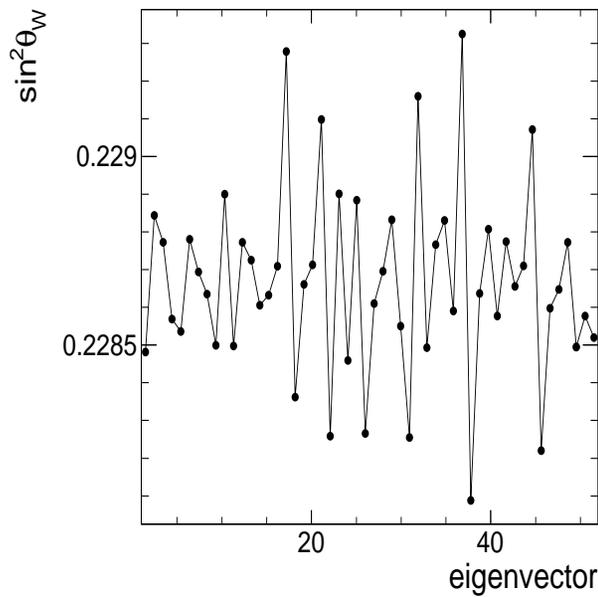
$\sin^2 \theta_{\text{eff}}$ Systematics

source	correction	uncertainty	comment
PDF	–	± 0.0013	PDF4LHC
FSR (QED)	–	± 0.0011	PHOTOS/Horace
LO model (EWK)	–	± 0.0002	ZFITTER
LO model (QCD)	$+0.0012$	± 0.0012	POWHEG
resolution and alignment	$+0.0007$	± 0.0013	misalignment
efficiency and acceptance	–	± 0.0003	data (symmetric)
background	–	± 0.0001	0.05% events
total	$+0.0019$	± 0.0025	

- "theory" systematics limited by PDFs and NLO (QCD) effects
- "detector" systematics is in the hands of experiments

Systematics 1: Partons and Their Dilution

- Follow PDF4LHC prescription, re-weight CT10-based MC: ± 0.0013
- CT10: $\Delta \sin^2 \theta_{\text{eff}} = \begin{matrix} +0.00130 \\ -0.00121 \end{matrix} (\sqrt{\sum |\Delta_i^\pm|^2})$, α_s negligible effect
- MSTW2008: $\Delta \sin^2 \theta_{\text{eff}} = +0.00048 \begin{matrix} +0.00039 \\ -0.00041 \end{matrix} (\sqrt{\sum |\Delta_i^\pm|^2})$
- NNPDF21: $\Delta \sin^2 \theta_{\text{eff}} = +0.00034 \begin{matrix} +0.00073 \\ -0.00073 \end{matrix}$ (rms of replicas)

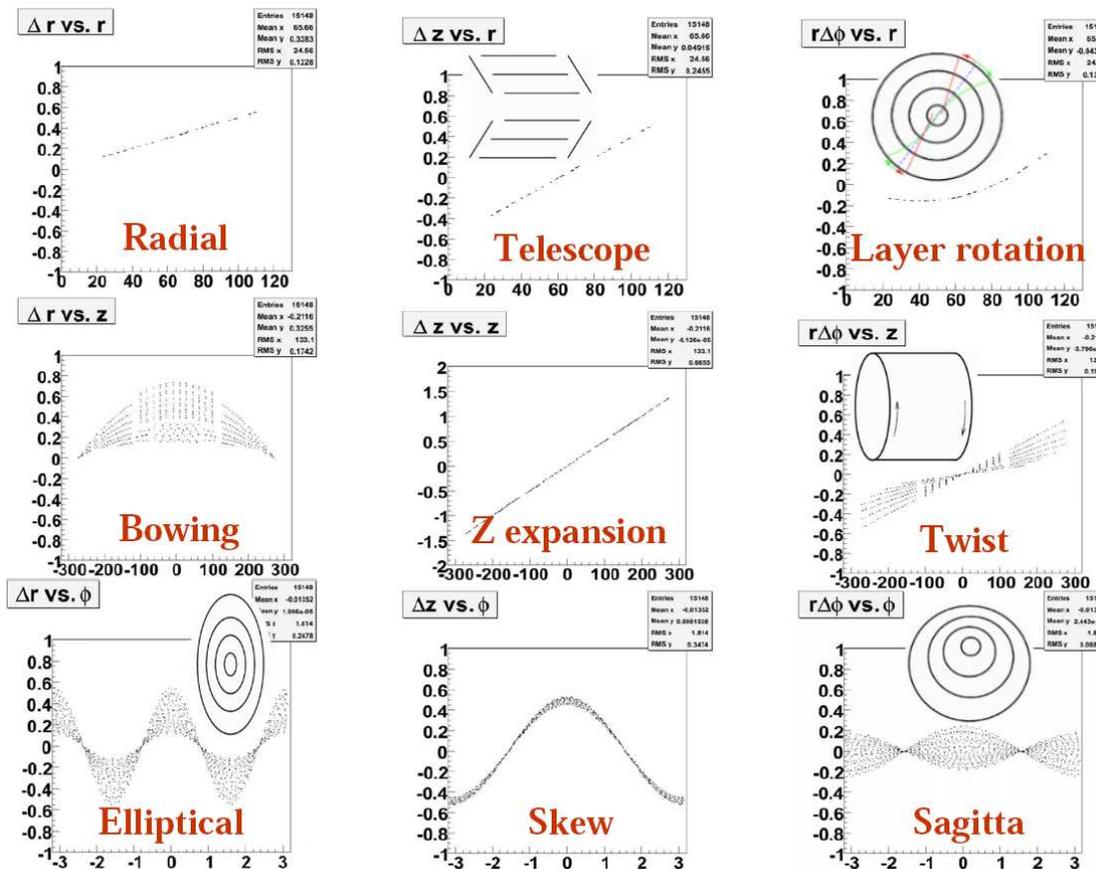


Systematics 2: NLO(QCD) and FSR(QED)

- NLO POWHEG with ideal detector (alignment/calibration)
 - difference from generated (0.0006 stat error)
 - variation with $p_T(\mu^- \mu^+)$ cut and/or reweighting
 - $\sin^2 \theta_{\text{eff}}$ within 0.0012
- FSR: study of four models (stand-alone): $\mathcal{R}(x)$
 - **Pythia** at LO (QCD) + **Pythia** or **PHOTOS** for FSR
 - **Horace** at LO (QCD) + $O(\alpha)$ or **higher-order** for FSR (best EWK)
 - $\sin^2 \theta_{\text{eff}}$ within 0.0011
 - **Horace** and **PHOTOS** agree better (0.0006 stat error)

Systematics 3: Resolution / Alignment

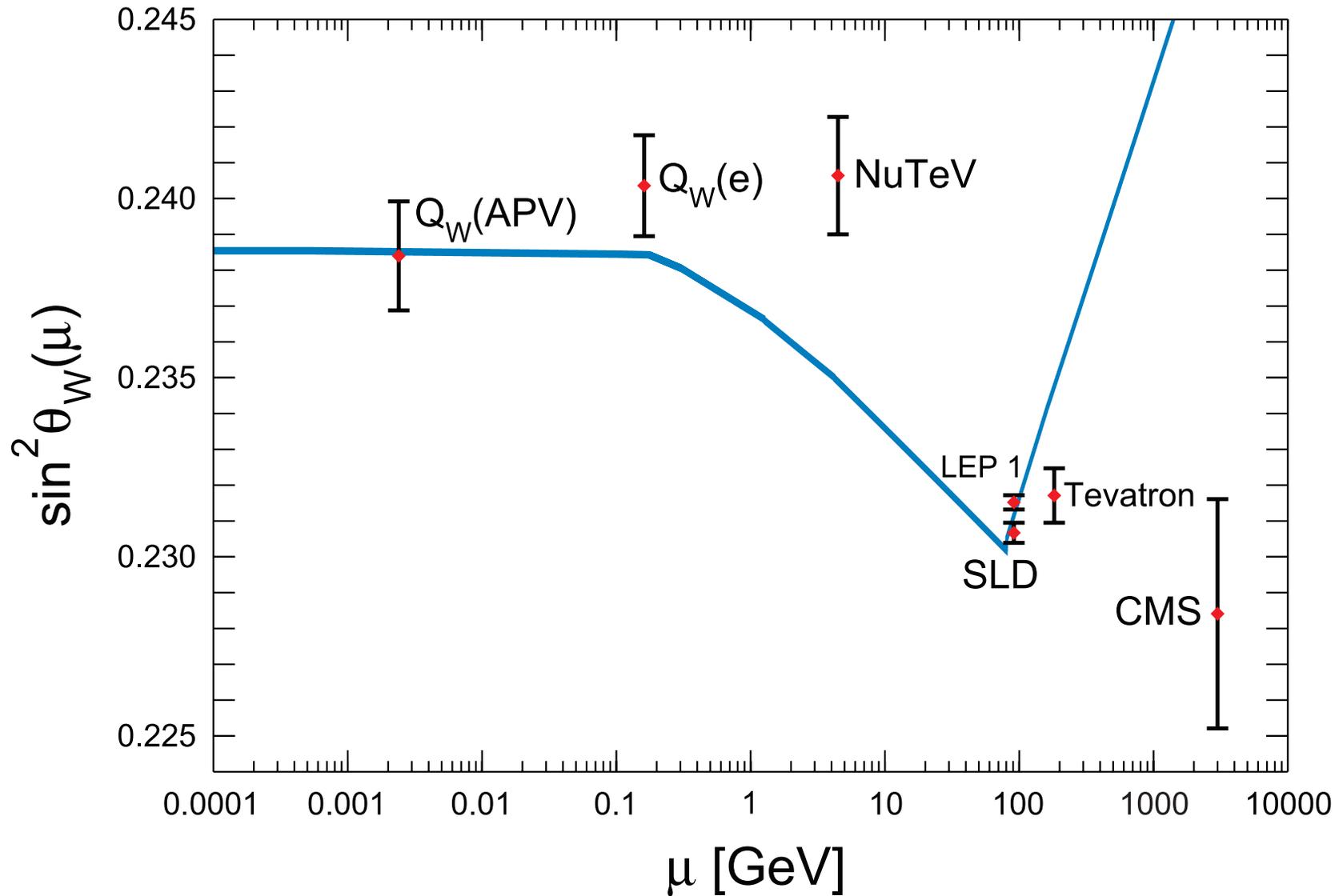
- Test Si Tracker misalignments and compare to data
 - test 9 basic distortions in cylindrical system ($\Delta r, \Delta z, \Delta \phi$ vs r, z, ϕ) and "realistic" cocktail of these; (e.g. $\Delta \phi$ vs r)
- Mass m bias vs $\cos \theta^*$ bias found to be a key measure



Summary

- $\sin^2 \theta_W$ is an interesting but **challenging** measurement at LHC
using $u\bar{u}$ & $d\bar{d} \rightarrow Z/\gamma^* \rightarrow \mu^-\mu^+$ and only 1 fb^{-1} at 7 TeV on CMS
$$\sin^2 \theta_{\text{eff}} = 0.2287 \pm 0.0020 \text{ (stat.)} \pm 0.0025 \text{ (syst.)}$$
- **Challenge 1: PDFs**
 - may improve, or can turn it around and use to constrain PDFs
 - be careful not to reuse the same info
- **Challenge 2: NLO model**
 - NLO "matrix element" and more variables
 - improved simulation, including higher-order EWK
- **Challenge 3: Detector effects**
 - will certainly improve, but not trivial
- In the end may trade statistics for systematics

Conclusion

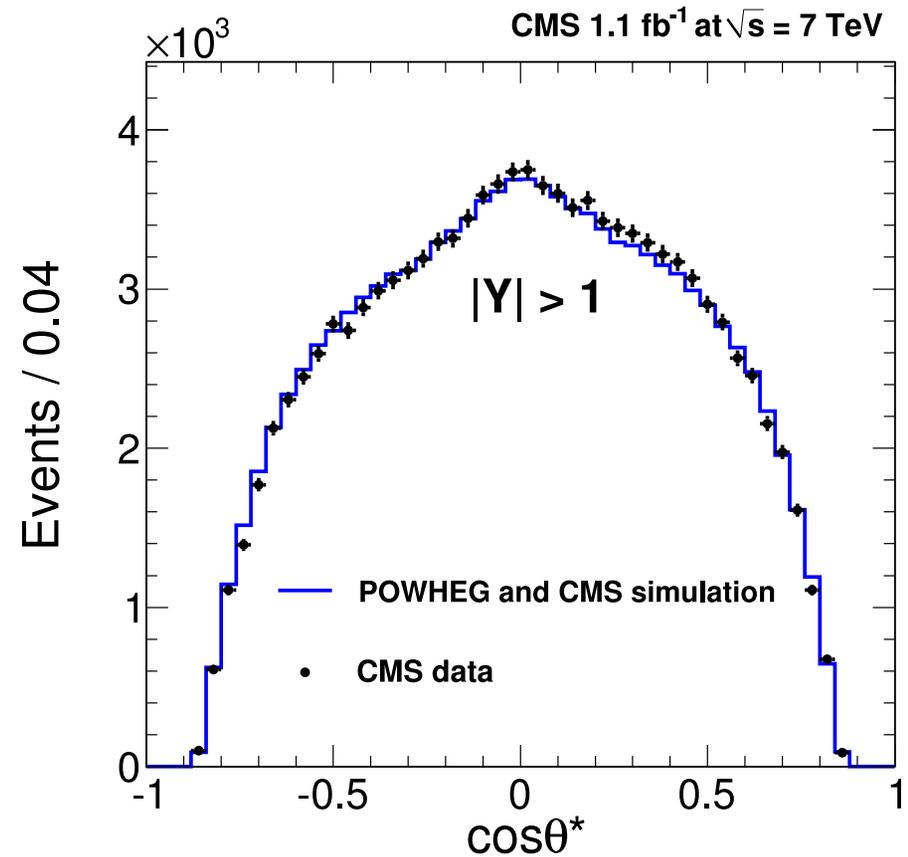
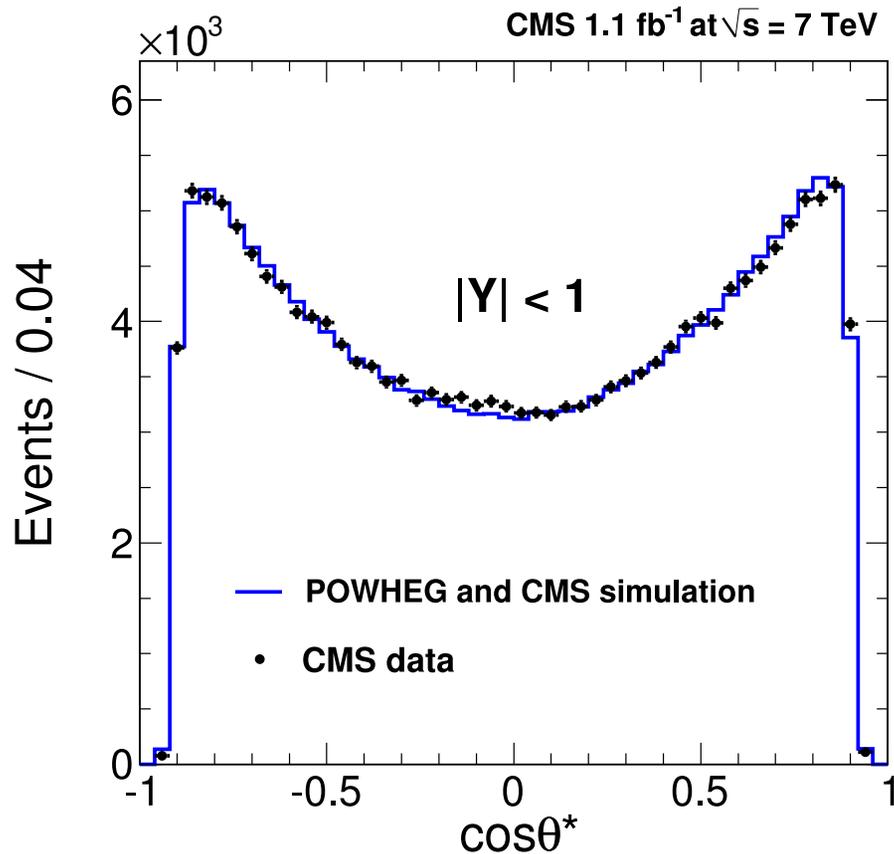


BACKUP

Challenges at LHC

- Challenges at LHC:

either dilution (smaller Y) or acceptance (larger Y) loss

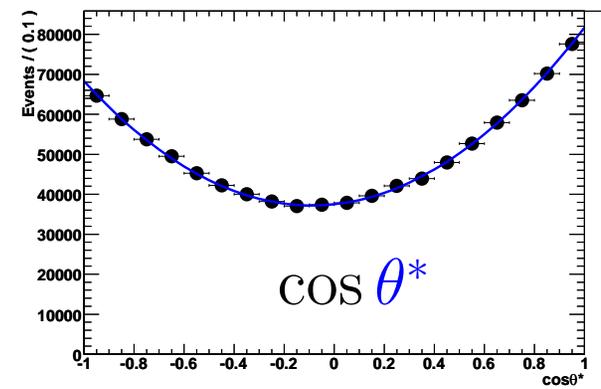
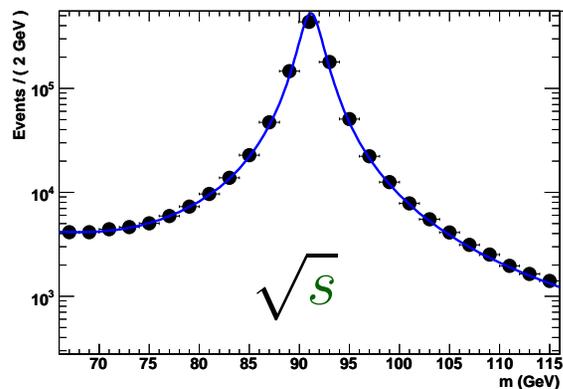
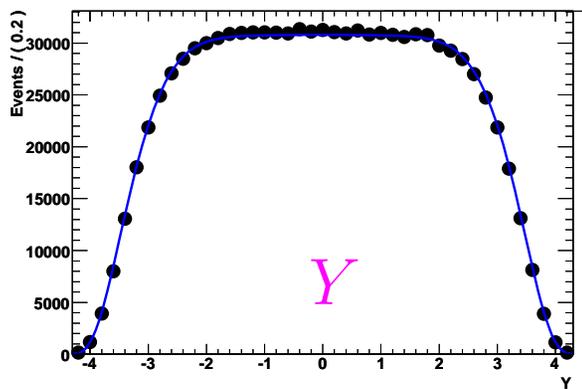


Building PDF+EWK Model

- Build Leading Order (LO) model
 - take LO EWK model $\hat{\sigma}_{q\bar{q}}(s, \theta^*)$ – from previous slides
 - take LO PDF $\tilde{f}_{q,\bar{q}}(x, Q^2)$ – from LO CTEQ6
 - correct fit results for NLO effects (e.g. with POWHEG)

$$\frac{d\sigma_{pp}(Y, s, \theta^*)}{dY ds d\cos\theta^*} \propto \frac{1}{s_{pp}} \sum_{q=u,d,s,c,b} \hat{\sigma}_{q\bar{q}}(s, \theta^*) \tilde{f}_q\left(e^Y \sqrt{s/s_{pp}}, s\right) \tilde{f}_{\bar{q}}\left(e^{-Y} \sqrt{s/s_{pp}}, s\right)$$

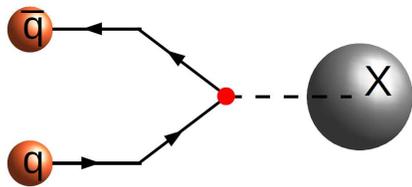
- Good agreement between LO simulation (Pythia) and the LO Model



$\sin^2 \theta_W$ and EWK Couplings

$$A(X_{J=1} \rightarrow f\bar{f}) \propto \epsilon^\mu \bar{u}_{q_1} \left(\gamma_\mu (\rho_1 + \rho_2 \gamma_5) + \frac{m_q}{\Lambda^2} \Delta q_\mu (\rho_3 + \rho_4 \gamma_5) \right) v_{q_2}$$

- Polarization amplitudes giving $f_{\lambda_1 \lambda_2} = \frac{|A_{\lambda_1 \lambda_2}|^2}{\sum |A_{ij}|^2}$



$$A_{\pm\pm} = -2 m_q \left(\pm \rho_1 + \frac{\beta M_X^2}{2\Lambda^2} (\rho_4 \mp \rho_3 \beta) \right) \rightarrow 0$$

$$A_{\pm\mp} = \sqrt{2} M_X (\rho_1 \pm \beta \rho_2)$$

- SM couplings:

$$\sin^2 \theta_{\text{eff}} \simeq \sin^2 \theta_W \simeq 0.2312$$

process	$\rho_1^{(X=\gamma)}$	$\rho_2^{(X=\gamma)}$	$\rho_1^{(X=Z)} = c_V(\theta_W)$	$\rho_2^{(X=Z)} = c_A(\theta_W)$
$X \rightarrow \ell^+ \ell^-$	$-e$	0	$\frac{-3+12 \sin^2 \theta_W}{6 \sin(2\theta_W)} e \simeq -0.045e$	$\frac{+1}{2 \sin(2\theta_W)} e \simeq +0.593e$
$X \leftarrow u\bar{u}, c\bar{c}$	$+2e/3$	0	$\frac{+3-8 \sin^2 \theta_W}{6 \sin(2\theta_W)} e \simeq +0.227e$	$\frac{-1}{2 \sin(2\theta_W)} e \simeq -0.593e$
$X \leftarrow d\bar{d}, s\bar{s}$	$-e/3$	0	$\frac{-3+4 \sin^2 \theta_W}{6 \sin(2\theta_W)} e \simeq -0.410e$	$\frac{+1}{2 \sin(2\theta_W)} e \simeq +0.593e$

Systematics: NLO EWK

- ZFITTER: effective $\sin^2 \theta_{\text{eff}}$ in on-shell scheme
(for $m_t = 175$, $m_H = 120$ GeV)

e	0.23152
mu	0.23152
tau	0.23152
up	0.23142
down	0.23129
charm	0.23142
strange	0.23129
bottom	0.23294

- Within ± 0.0002 (can ignore bottom, no A_{FB})